C. Continuous Medium Theory Applied to Viscoelastic Strain Analysis, II

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A study program of solid propellant viscoelastic physical properties is being formulated from a different point of view. The apparently divergent previous studies (*QSR 38-3* through *QSR 38-9*) shall now begin to converge with this report. Since our approach to the problem of viscoelasticity is somewhat different from the approach used by the majority of investigators, seemingly unrelated parallel studies will be conducted in the future to either confirm or deny the hypotheses used in this study. The study reviewed in this report was presented last October at the 33rd annual meeting of the Society of Rheology (Ref. 14). Since the basic ideas incorporate a relatively unfamiliar complement of higher mathematics and experimentation, other investigators should not extrapolate conclusions until any discrepancies that may arise in the immediate future are resolved.

A preliminary introduction to Continuous Medium Theory was presented in *QSR 38-7*. Studies were initiated to determine the applicability of Continuous Medium Theory to propellant viscoelastic strain analysis. Topics discussed introduced concepts pertaining to: the physical significance of a strain energy function W with respect to propellant, a hypothesis specifying $\varepsilon_{33} = 0$ on the boundary at the free end surface of a biaxially pressurized propellant grain specimen, a comparison of this hypothesis with the generally accepted assumption that ε_{33} is equal to an average structural strain, the relationships between the various cartesian strain invariants, I_1, I_2, I_3, and, finally, the introduction of time dependency into the strain energy function.

This report will review the mathematics involved and the experimental data that are necessary to evaluate the strain energy function W. The amenability of the photoelastic coating technique (*QSR 38-3* through *38-9*) to Continuous Medium Theory is apparent since the underlying mathematical assumptions regarding "point" strains in the theory are satisfied by the technique. Experimental correlations between triaxial point strains and the strain energy function as a function of time will be reported at a later date.

1. Further Observations

The strain energy function will continue to be expressed in terms of two longitudinal surface strain hypotheses ($\varepsilon_{33} = 0$; ε_{33} = average structural strain) for the measured longitudinal principal strain (ε_{33}) for the time being (*QSR 38-7*). Comparisons with derived strain energy functions studied at this Laboratory using these assumptions will eventually be compared to analogous strain energy functions obtained under different assumptions, e.g., Refs. 15, 16, 17.

The importance of an explicit experimental strain hypothesis is evident if the generally accepted mathematical interpretation of physical properties based on a point strain concept is to be utilized. The experimental difficulty of measuring the three principal strains at a point region in a solid propellant has not as yet been completely overcome. It is common practice for investigators to choose specific structures, e.g., JANAF tensile bars, and assume strain relationships based on homogeneity, isotropy, etc. Usually an experimentalist assumes some form of a stress-strain law to be valid. This law may be represented by a set of constitutive equations. The law will inherently define certain relationships to exist between the various principal strains. Apart from the fact that the law may also contain some inherent assumptions as well, e.g., homogeneity, isotropy, or linearity, which are violated by the real material, it is also possible that the experimental stress-strain relations cannot be fulfilled except by allowing one or more of the constants of the assumed stress-strain law to become a variable, e.g., a variable Poisson's ratio. Under these circumstances it would appear that the initial assumption of the law is not correct, and thus use of the initial equations is not entirely justified except as an *ad hoc* relationship with no explicit theoretical basis.

Another difficulty is that boundary effects always exist, and while there may be ways of avoiding them, it seems unwise or unwary to attempt to describe physical behavior without first insuring that these extraneous effects are either truly negligible or are properly accounted for in the theoretical description or analysis of the experiment.

It has been observed that boundary effects are commonly neglected in the propellant literature. All experimental data (deformations of structure) inadvertently contain these effects to some degree. One alternative commonly employed is to make certain strain measurements, average them, and apply them to a defined area or volume. The JANAF tensile bar experiment is an example.

A difficulty is sometimes encountered in the use of average or structural strains in lieu of point strains. While it is true that the over-all deformation is merely the

integrated result of all strains, it is not precise to take the average deformation as equal to the point strains. In the literature, such boundary effects are ignored regardless of the problem under investigation.

It has been observed at this Laboratory and elsewhere that, for even a tensile bar, the two principal strains vary somewhat both in direction and magnitude at various points on the propellant surface within the nominal gage length. The primary cause of this observation is probably due in part to sample preparation (machining, Ref. 18) or inadequate instrumentation. Observations of physical failure surfaces, such as the fractured jagged surface of a tensile bar, indicate that the principal strain fields possibly rotate, or that the individual principal point strains constantly change in magnitude, or both. It is noted that the mechanics of fracture is generally indeterminate. In summary, even with this relatively simple experiment, a variably stressed structure was employed in conjunction with a theory derived for point analysis.

To avoid some of the above difficulties, the experimentalist should: (1) use a relationship between stress and deformation which is as unrestrictive as possible (the strain energy function W, discussed below, will be used), (2) examine test specimens carefully for boundary effects and try to either eliminate them or learn how to live with them by reducing their effect on measurements or by accounting for them in the stress-strain relationship, and (3) use a point strain and stress measuring technique.

An experimental requirement which satisfies the assumptions underlying the mathematics of a strain concept is that each of the three principal strains be measured in a point region of the material. Approximations to this

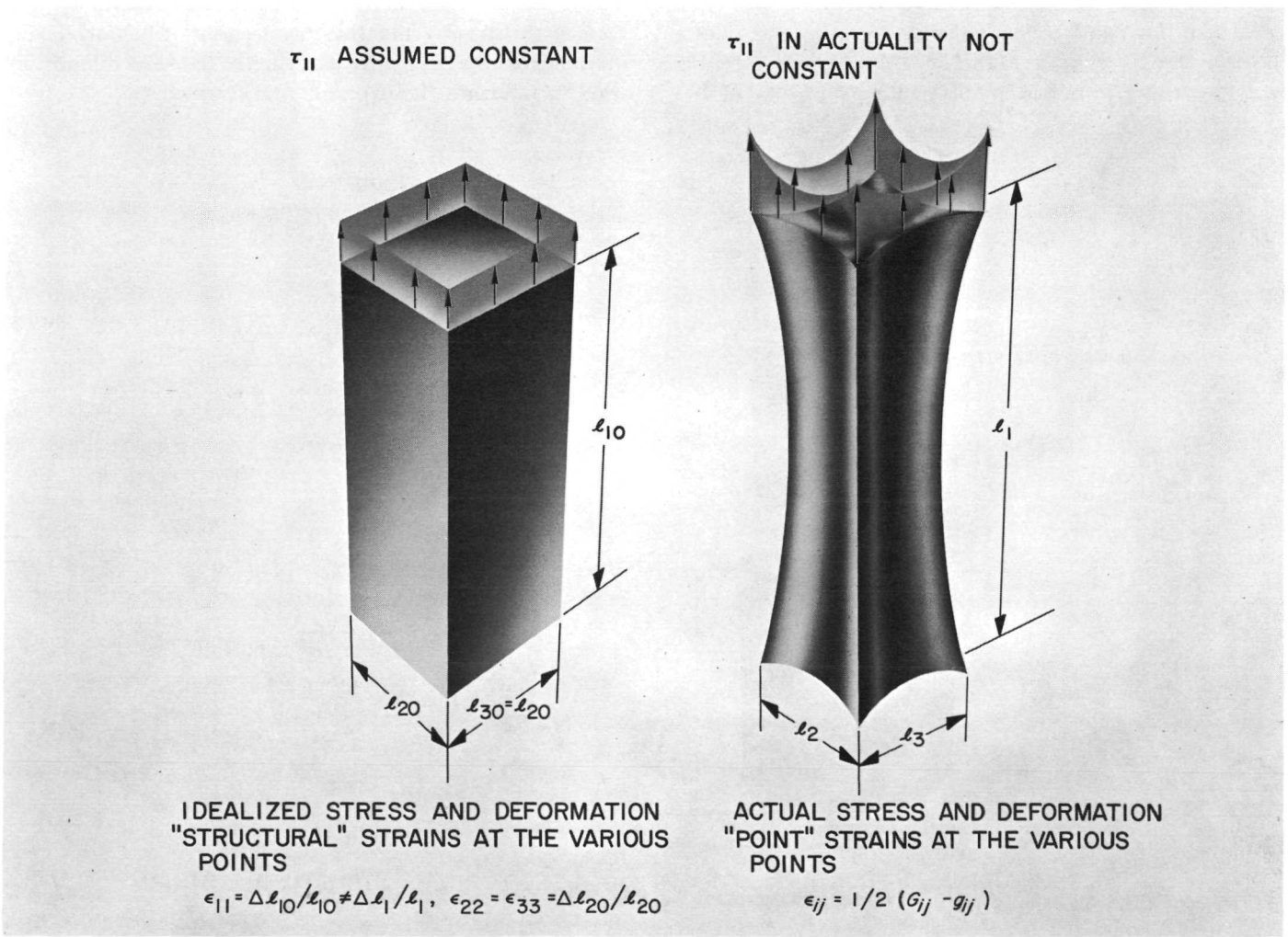

Fig. 10. Exaggerated deformation comparisons of tensile bars at large strain levels

requirement are found in contemporary bi- and tri- axial experiments (Ref. 19). Usually in these experiments two structural deformation measurements are made, and the three principal point strains are deduced by assumptions. In some,propellant physical property experiments, most, if not all measured principal strains are in actuality average structural strains, i.e., boundary deformations are measured. Fig. 10 illustrates an exaggeration of this statement for a tensile experiment. Needless to say, for such an experiment the concise geometric expression for volume is indeed quite difficult to express mathematically in terms of principal point strains. These actual strains are usually erroneously presumed constant in direction and magnitude at any point throughout the structure, although, in the aggregate, this discrepancy may be trivial for macroscopic analysis.

Problems relating experimental strain to mathematical strain are being reviewed at this Laboratory. Currently it is found that measurement of biaxial point principal surface strains can be accomplished by using the photoelastic coating technique (*QSR 38-3* through *38-9*). However, the third principal point strain measurement has not as yet been resolved and is a problem under current investigation. For expediency, until the aforementioned problem is solved, the third principal strain shall be taken as equal to the average structural longitudinal strain $\varepsilon'_{33} = \Delta l'_{33}/l'_{33}$, Hypothesis I (Fig. 11); and as being equal to zero at the free end surface of the biaxially pressurized grain $\varepsilon_{33} = 0$, Hypothesis II. These two hypotheses define the extreme values that the longitudinal strain can assume. It is noted that experimental circumstantial evidence exists that favors Hypothesis II. However, for the present time both hypotheses will be used with impartiality. The current extensometer used to measure this longitudinal structural strain is shown in Fig. 12. One should be aware of the experimental observation that an unrestricted biaxially pressurized cylinder bows in the center (Fig. 11). This effect is quite apparent for an unrestricted 5-in. D and 5-in. long propellant grain. If a small specimen is used in an experiment, naturally these extraneous effects are not obvious. However, they still exist and must be accounted for in the mathematical concept of strain. Thus the strain energy function development reported below will explicitly state the hypothesis used to interpret the experimental strain data.

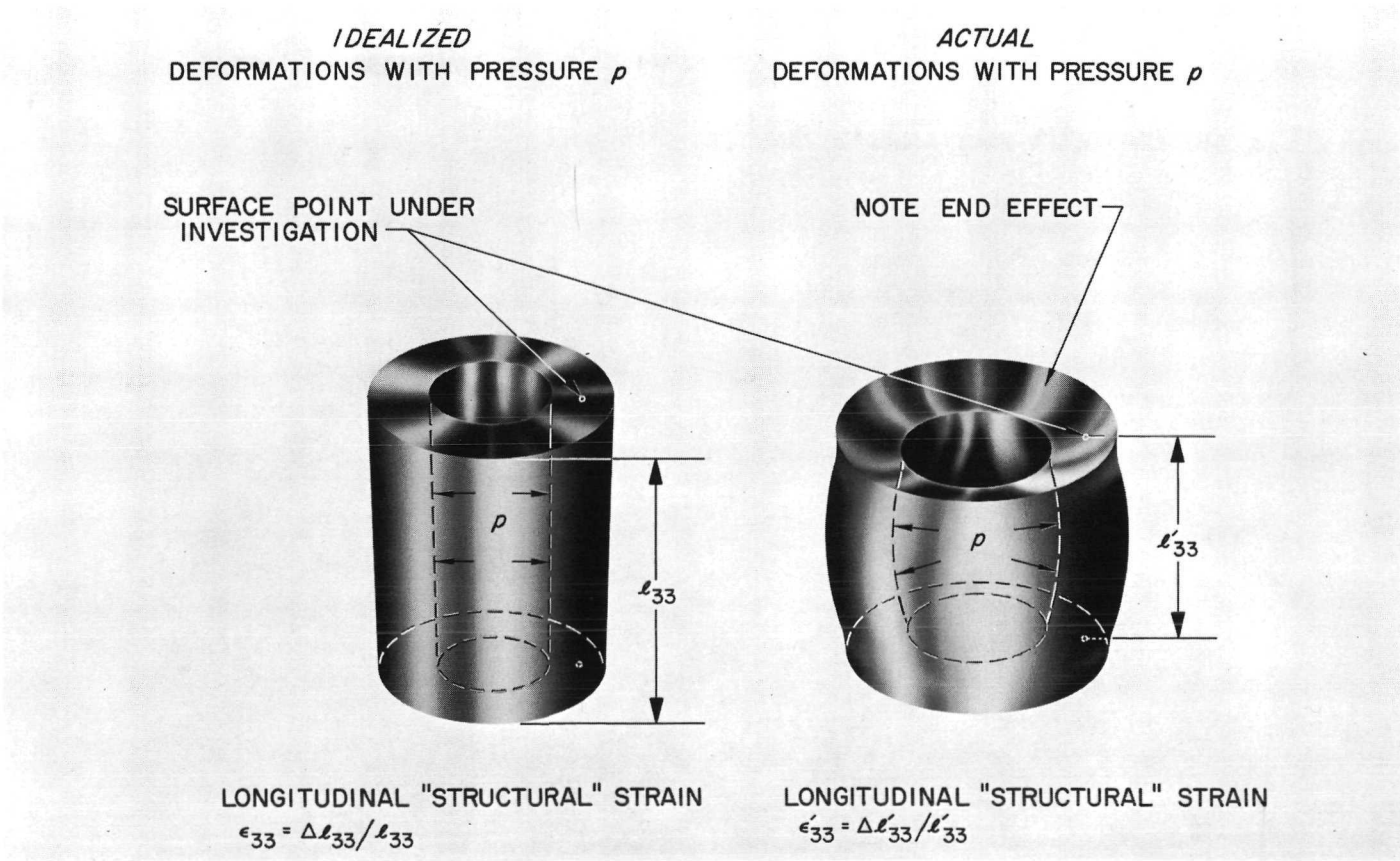

Fig. 11. Exaggerated deformation comparisons of an unrestricted thick wall cylinder at large strain levels

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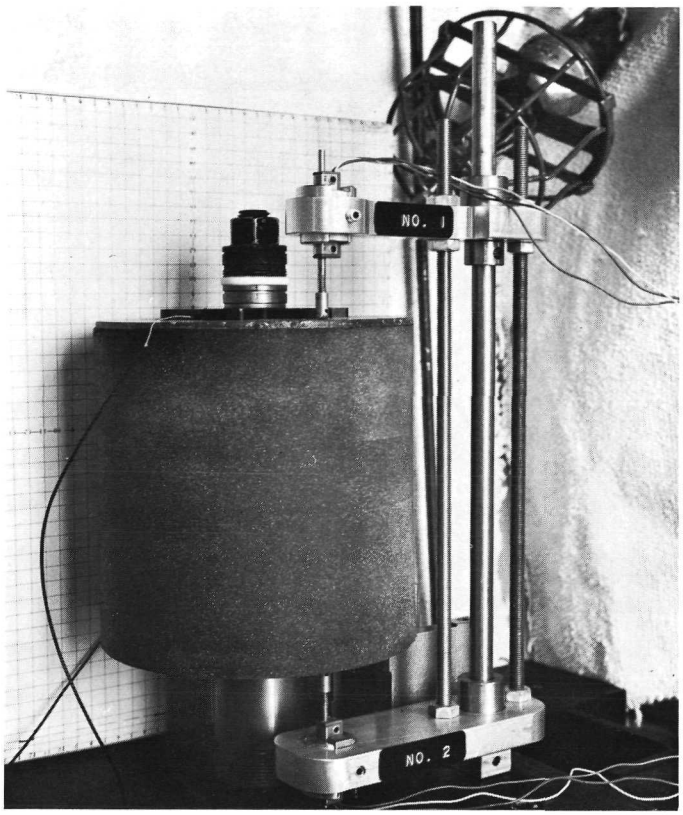

Fig. 12. Longitudinal extensometer to measure cylinder contraction and end deformations

2. The Derivation of the Strain Energy Function W

Experimental evidence is found in Ref. 20 for PBAA propellant that is in agreement with observations for polyurethane propellant; namely, that solid propellant exhibits a complete time-dependent elastic recovery when unloaded. Agreement is also found in Ref. 21 with observations for polyurethane propellant: this propellant will phenomenologically reheal itself. Creep data obtained at this Laboratory substantiate these preceding remarks. These two observations tend to encourage the concept that a time-dependent strain energy function may describe the viscoelastic[1] physical properties of solid propellant. There is good reason to believe that solid propellant inherently exhibits a recoverable memory which is analogous to a time-dependent strain energy function. The mathematical derivation of such a strain energy function is presented below for any given instant in time. At a later date, these equations will explicitly include a time function. Experimental data is currently being accumulated for this purpose.

In *QSR 38-7* it was proposed that the constitutive equation for a continuous medium of solid propellant (in the macroscopic sense) be

$$\tau^{ij} = \frac{1}{2}\left(\frac{g}{G}\right)^{1/2}\left\{\frac{\partial W}{\partial I_1}\left(\frac{\partial I_1}{\partial \varepsilon_{ij}} + \frac{\partial I_1}{\partial \varepsilon_{ji}}\right) + \frac{\partial W}{\partial I_2}\left(\frac{\partial I_2}{\partial \varepsilon_{ij}} + \frac{\partial I_2}{\partial \varepsilon_{ji}}\right) + \frac{\partial W}{\partial I_3}\left(\frac{\partial I_3}{\partial \varepsilon_{ij}} + \frac{\partial I_3}{\partial \varepsilon_{ji}}\right)\right\} \quad (1)$$

where

τ^{ij} = contravariant stress tensor

$g = |g_{mn}|$ = covariant metric tensor (unstrained state; g is the determinant of the array g_{mn}

$G = |G_{mn}|$ = covariant metric tensor (strained state; G is the determinant of the array G_{mn})

$W(I_1, I_2, I_3, x) = \rho U(I_1, I_2, I_3, x)$ = elastic potential per unit volume of the unstrained body

ρ = density of the propellant

$U(I_1, I_2, I_3, x)$ = internal energy in the classical thermodynamic (thermostatic) sense

x = independent variable such as entropy or time

I_1, I_2, I_3 = strain invariants. For the deformation where a cube deforms into a cuboid and the material and space coordinates are cartesian

$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$

$I_2 = \lambda_1^2\lambda_2^2 + \lambda_1^2\lambda_3^2 + \lambda_2^2\lambda_3^2$

$I_3 = \lambda_1^2\lambda_2^2\lambda_3^2$

$\lambda_i = 1 + \varepsilon_{ii}$ = extension ratios

$\varepsilon_{ij} = \varepsilon_{ji}$ = finite strain tensor

This equation was derived by assuming that the constitutive equation for solid propellant can be reasonably expressed in the form

$$\tau^{ij} = \rho \frac{\partial U}{\partial \varepsilon_{ij}} \quad (2)$$

It is noted that the time element can be arbitrarily introduced into Eq. (2) by simply suggesting that

[1]In the propellant field there is a tendency to describe time-dependent physical properties as being viscoelastic. It should be pointed out that in the field of rheology, time-dependent physical properties may be described as being anelastic, plastic-dynamic, etc. (Ref. 22).

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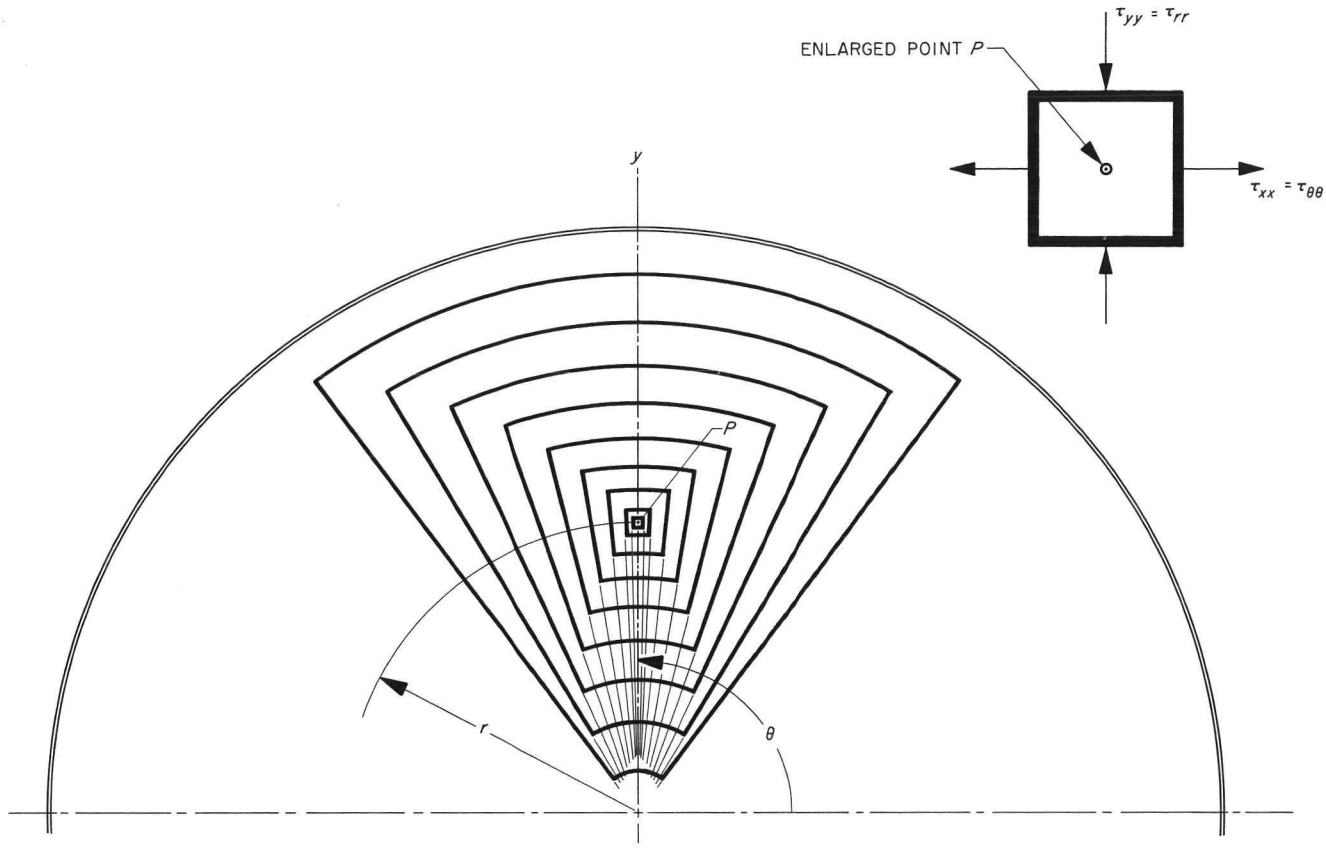

Fig. 13. An infinitesimal cube within a structure normally described by curvilinear coordinates

$U = U(t)$. All that was done here was to assume that the independent variable is time-dependent. This approach is sound, since any constitutive equation is of an intrinsic nature and can only make sense if the physical material under investigation happens, perchance, to satisfy the postulated relationships. A comprehensive treatise of this entire subject is found in Ref. 23.

Thus, if for the present, only the isochronal case is considered, and the stress-strain response of a cube into a cuboid is observed, then Eq. (1) reduces to

$$\tau_{ij} = \frac{1}{(I_3)^{1/2}}\left\{\frac{\partial W}{\partial I_1}\frac{\partial I_1}{\partial \varepsilon_{ij}} + \frac{\partial W}{\partial I_2}\frac{\partial I_2}{\partial \varepsilon_{ij}} + \frac{\partial W}{\partial I_3}\frac{\partial I_3}{\partial \varepsilon_{ij}}\right\} \quad (3)$$

The stress-strain response of various classes of continuum, such as rubbers, may be reasonably described by a constitutive equation of this form (Ref. 24, 25).

Ideally this constitutive equation is applicable to materials that exhibit perfect elasticity. Its superiority to classical elasticity is founded on its capability to incorporate both physical and geometric nonlinearity (Ref. 23). In addition, this constitutive form may also be empirically exploited for materials whose energy function is dissipated in some prescribed manner.

For an isotropic material subjected to a three-dimensional strain field Eq. (3) reduces to six equations containing 33 unknowns (6 stresses, 6 strains, 18 invariant gradients, and 3 potential gradients). The strain energy function W must experimentally satisfy all six of these equations. Thus, the experimental task was to obtain a sufficient number of values for the 30 physical parameters at various points on a medium in order to be able to solve for the three potential gradients

$$Ю = \frac{\partial W}{\partial I_1}, \quad И = \frac{\partial W}{\partial I_2}, \text{ and } \quad Я = \frac{\partial W}{\partial I_3}$$

Our approach will be to work directly from Eq. (1) using a relatively complex three-dimensional strain problem. The structure to be investigated is a radially pressurized, unrestricted thick-walled cylinder. This geometry was chosen because the principal stresses at a point may be reasonably approximated for finite strains (to 30%) independently of the medium's physical properties. The

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major change in approach from that of earlier work, is that two of the three principal strains are not computed from boundary motions (i.e., from structural deformations), which shall be called structural strains. Instead, biaxial principal strains are measured *at a point* on the cylinder end surface, using a birefringent, low-modulus coating. The third principal strain, always relatively small, was measured as a structural strain by following the axial motion of the cylinder with an extensometer. The entire data reduction process, tedious but not complex, was amenable to computer solution for obtaining the magnitudes of Ю, И, Я at various points on the cylinder. The strain energy function W was then calculated from these gradients for a polyurethane propellant.

3. Stresses

To be consistent with point analysis, it would be necessary to know the principal stresses at the same point that the strains are measured. Experimentally, only structural boundary stresses may be measured with any degree of accuracy. Although there are internal stress-measuring devices currently available (e.g., various semiconductors), most suffer from not being able to measure explicitly the true principal stresses and their directions. One fault of these gages is that they introduce unknown discontinuities (stress concentrations) in the medium under investigation. Therefore, it would be expedient to design an experiment where only the external structural boundary stresses (applied loadings) are measured and the internal point boundary stresses are calculated; with respect to an infinitesimal cuboid. This may be accomplished by taking advantage of the fact that in the limit, principal stresses at a point in curvilinear coordinates are identical to principal stresses in cartesian coordinates. It can be shown that such a multiaxial principal stress field at a point which describes the boundary stresses of an infinitesimal cuboid may be described for a structure whose geometry is normally characterized in terms of curvilinear coordinates.

The only reason to choose a curvilinear system for a symmetrical geometry is that it is simpler to express the boundary conditions of a vector field in natural coordinates. There is no reason to generalize our thinking to a curvilinear system for the geometry in question, a thick-walled cylinder.

Upon examination of Fig. 13, one notes that in the limit, the orthogonal net dr, $rd\theta$ approaches dx, dy. By definition, τ_{ii} is a tensor unique to the point under investigation. It is also recalled that the scalar value of a tensor is invariant with respect to the reference coordinate system. Thus, at a point

$$\tau_{xx} = \tau_{\theta\theta} \ , \ \tau_{yy} = \tau_{rr} \ , \ \tau_{zz} = \tau_{zz}$$

Consider the classical theoretical equations for an internally pressurized unrestricted thick wall tube subjected only to a biaxial radial pressure (Fig. 14). The equations that describe the stress state at various points *independent of the medium's physical properties are*

$$\overset{i}{\tau}_{11} = \frac{a^2 p}{b^2 - a^2}\left(1 + \frac{b^2}{y_i^2}\right)$$

$$\overset{i}{\tau}_{22} = \frac{a^2 p}{b^2 - a^2}\left(1 - \frac{b^2}{y_i^2}\right)$$

$$\overset{i}{\tau}_{33} = 0 \qquad (4)$$

where

$\overset{i}{\tau}_{11}, \overset{i}{\tau}_{22}, \overset{i}{\tau}_{33}$ = point principal stresses at i

a = inner radius of cylinder

b = outer radius of cylinder

p = radial internal pressure

y_i = radial length to point under investigation

Strictly speaking, these equations[2] may be exactly valid only for infinitesimal strains. It is noted that Eq. (4) was derived by selecting a stress potential that explicitly satisfied the equilibrium equations. The compatibility equations for infinitesimal strains were then used to select a specific potential. But the specific potential function selected does not necessarily satisfy the compatibility equations for finite strains. No attempt has been made in this report to verify this specific function because of the complexity of the finite compatibility equations.

[2]It has been argued that these equations hold only for a plane uniform deformation (plane strain) in the longitudinal direction. This is *not* true. In the plane stress derivation, the components u, v, w of the displacement vector are not in general independent of z. Thus the plane stress problem is not a truly two-dimensional problem. From the equilibrium equations (by Airy Stress function) one obtains stresses in terms of three constants and two boundary conditions. It is at this point that inspection of the plane strain restriction reveals that one of the constants must be zero in order to satisfy single valueness for the displacement. However, this latter restriction should have been obvious since a real material is being used that contains no significant discontinuities in the macroscopic sense.

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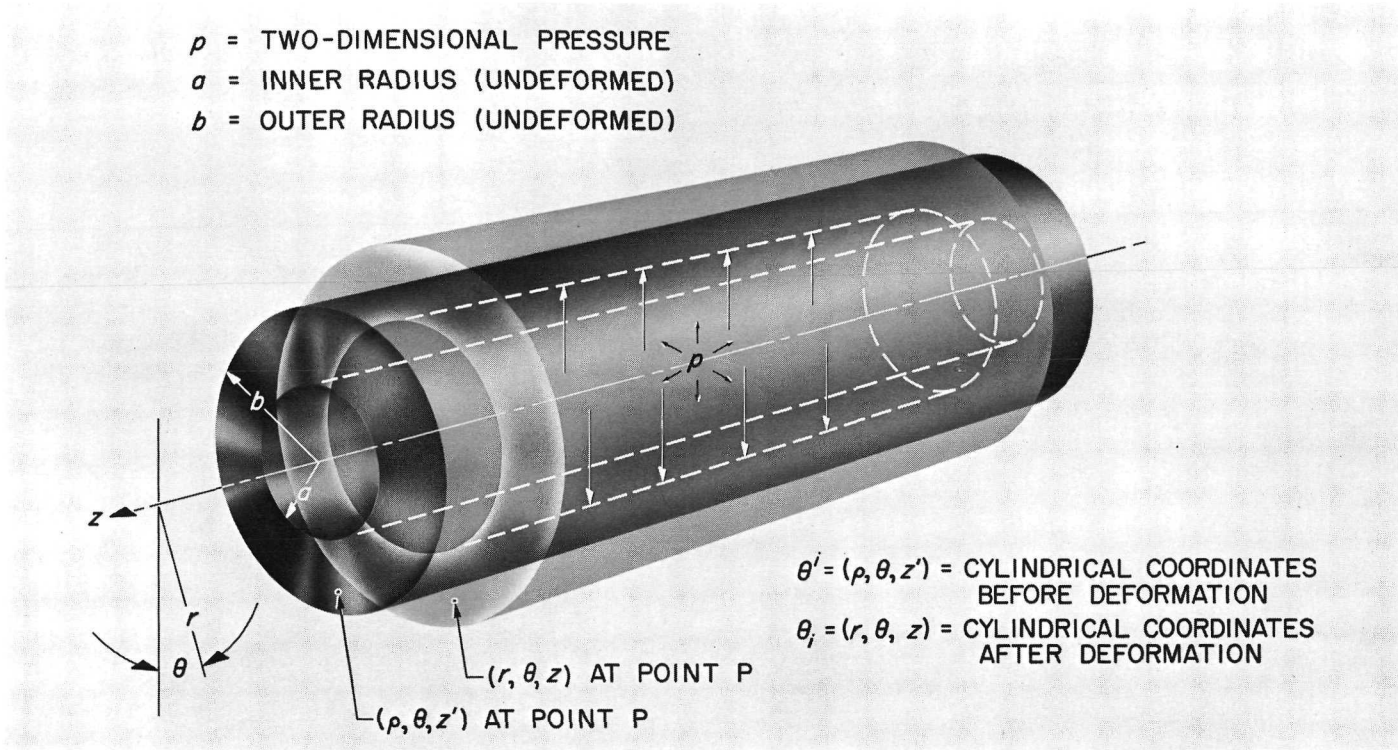
p = TWO-DIMENSIONAL PRESSURE
a = INNER RADIUS (UNDEFORMED)
b = OUTER RADIUS (UNDEFORMED)
θ' = (ρ, θ, z') = CYLINDRICAL COORDINATES BEFORE DEFORMATION
θ_i = (r, θ, z) = CYLINDRICAL COORDINATES AFTER DEFORMATION
(r, θ, z) AT POINT P
(ρ, θ, z') AT POINT P

Fig. 14. Idealized deformations of a biaxially pressurized unrestricted thick wall cylinder

On the other hand, the magnitude of internal stress errors that may be introduced because of finite strains (to 30%) should in all probability be negligible. This is because the equilibrium equations are satisfied at the boundaries regardless of the strain magnitude. Since the stresses are continuously increasing or decreasing, the mode between the boundaries would not be expected to deviate significantly. In any event, it is surmised that Eq. (4) would be applicable to finite strains if an iteration of the dimensions a and b is performed from strain level to strain level. Thus, point stresses can be obtained from the applied pressure, the cylinder dimensions, and the point coordinates.

Unpublished experimental studies of contained grains at this Laboratory have indicated that this potential function seems to satisfy the compatibility equations for strain magnitudes of at least 15%. The least qualifying argument in favor of the stress potential approach is that most of the popular analytical and experimental conclusions regarding structural analysis of rocket grains (static or viscoelastic) are based on such an approach. It is noted at this point that an infinitesimal stress-measuring device is under current study at this Laboratory to resolve this question.

4. The Concept of Strain (Ref. 23)

Care must be taken to not apply "strain" data indiscriminately to Eq. (3). Experimental strain data must conform to the metric tensor both before and during deformation. This required congruency arises from the mathematical definition of strain. This definition is not simply

$$\varepsilon_{mn} = \frac{\Delta l_{mn}}{l_{mn}} \tag{5}$$

but

$$\varepsilon_{mn} = \frac{1}{2}(G_{mn} - g_{mn}) \tag{6}$$

In continuum theory, the strains are defined as being one-half the difference of the corresponding components in the deformed G_{ij} and undeformed g_{ij} metric tensors (Ref. 24). The physical significance of such a definition is vague except for the strain representation of a cube

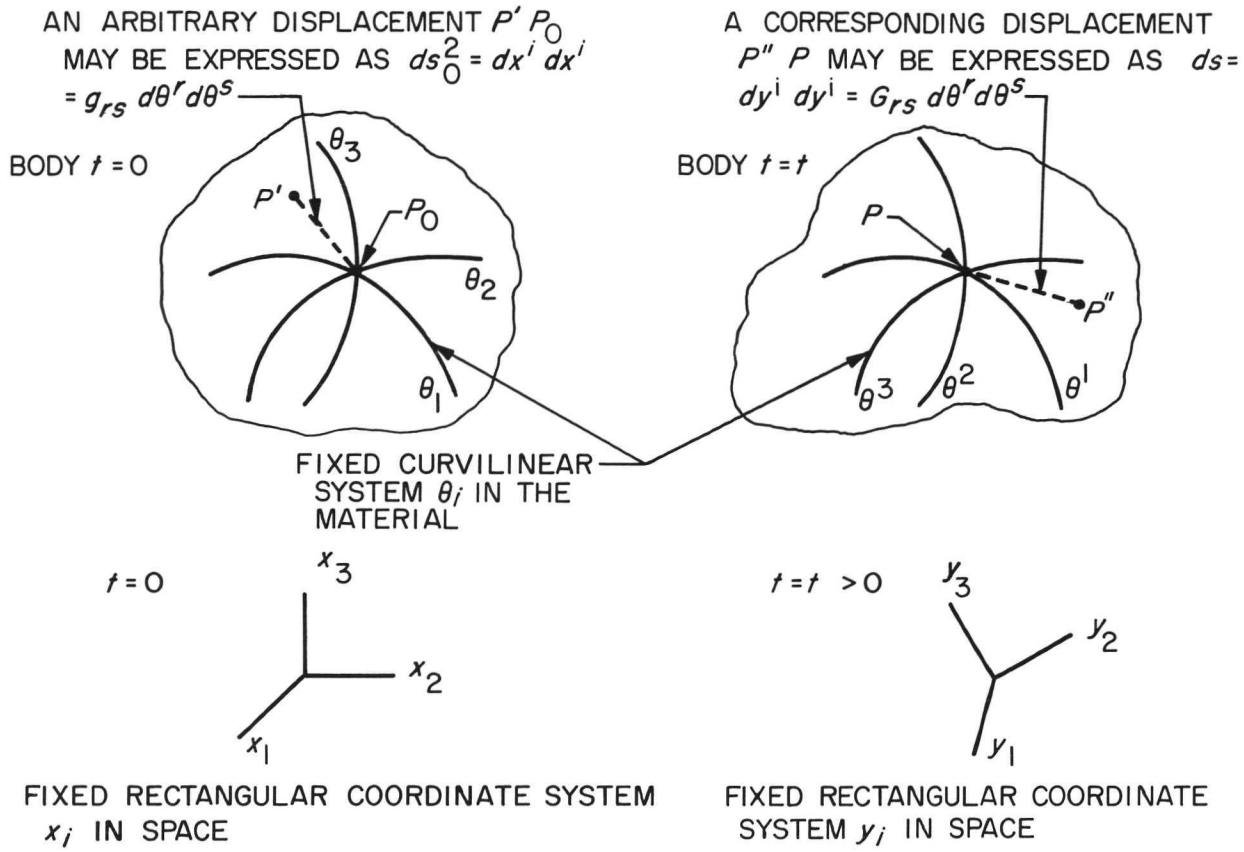

Fig. 15. The geometric concept of strains in a Euclidean space

which deforms into a cuboid in cartesian coordinates. Mathematically the strain is then defined for the irrotational condition as

$$\varepsilon_{11} = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial u}{\partial x}\right)^2$$

$$\varepsilon_{22} = \frac{\partial v}{\partial y} + \frac{1}{2}\left(\frac{\partial v}{\partial y}\right)^2$$

$$\varepsilon_{33} = \frac{\partial w}{\partial z} + \frac{1}{2}\left(\frac{\partial w}{\partial z}\right)^2 \qquad (7)$$

where u, v, and w are the displacement components of the points on the body being deformed.

A distinction is here made between the point strain defined by Eq. (7) and the structural strain that is usually measured in the laboratory. As pointed out by Rivlin (Ref. 25), "One of the major difficulties is to perform an experiment of desired pure homogeneous deformations which is uncomplicated by end (boundary) effects." To circumvent the distinctions between point and structural strains requires that strain measurements be made at a point in or on the medium being examined. The magnitude of such a measured strain must equal ε_{ii} and satisfy the displacement gradients.

Following the same line of reasoning presented above for stresses, it is obvious that the point strains in a pressurized cylinder may be reasonably described in terms of an infinitesimal unit cube structure that deforms into a cuboid of extensions λ_1, λ_2, λ_3.

At this point attention is brought to Ref. 26. An excellent introduction to tensor calculus and engineering solutions of such mathematics is found in this reference, which can facilitate the interpretation of the voluminous mathematical theory available in the literature and in Refs. 14–29.

The mathematical concept of strain is generally presented as follows: Figure 15 illustrates two points P_0

and P existing in a Euclidian space. It is assumed that P at time t is related to P_0 at time $t = 0$ by

$$y_i = y_i(x_1, x_2, x_3, t)$$

$$x_i = x_i(y_1, y_2, y_3, t) \tag{8}$$

Obvious assumptions regarding single-valueness and continuous differentiability are made. It is also assumed that differentials dy^i, evaluated at some time t, may be expressed in terms of differentials dx^j by

$$dy^i = \frac{\partial y^i}{\partial x^j} dx^j \quad , \qquad dx^i = \frac{\partial x^i}{\partial y^j} dy^j \tag{9}$$

In tensor calculus a distinction is made between subscripts and superscripts on differential variables. The former is associated with covariant differentiation and the latter with contravariant differentiation. In a rectangular coordinate frame, no distinction is made between covariant and contravariant tensors.

As the body is deformed, depending on its physical properties, arbitrary points P' about P_0 and P'' about P are relatively relocated in some manner in the displacement process giving rise to $ds \neq ds_0$. The propellant is said to be strained in the ds position.

In mathematical terms the dot product of the base vectors to an orthogonal net (frame or system) is equal to the square of the length of the vector P_0P' and PP''. Thus

$$|P_0P'| = ds_0 \ , \ |PP''| = ds \tag{10}$$

and

$$ds_0^2 = dx^i dx^i$$

$$ds^2 = dy^i dy^i \tag{11}$$

where dy^i are evaluated for a fixed time t and are related to dx^j by Eq. (9).

The original propellant is shown in Fig. 14 to be described by general curvilinear coordinates θ_i. Note that in this system θ_i is Lagrangian in character since the system is attached to point P during the deformation process.

$$x_i = x_i(\theta_1, \theta_2, \theta_3) \tag{12}$$

One can easily observe that in the straining process the curvilinear system can be expressed at any instant t by Eq. (12), (13), (14), and (15).

$$y_i = y_i(\theta_1, \theta_2, \theta_3, t) \tag{13}$$

Analogous to Eq. (9)

$$d\theta^i = \frac{\partial \theta^i}{\partial x^j} dx^j \qquad d\theta_i = \frac{\partial x^j}{\partial \theta^i} dx_j$$

$$dx^i = \frac{\partial x^i}{\partial \theta_j} d\theta^j \qquad dx_i = \frac{\partial \theta^j}{\partial x^i} d\theta_j \tag{14}$$

and from Eq. (9)

$$dy^i = \frac{\partial y^i}{\partial \theta^j} d\theta^j \quad , \quad d\theta^i = \frac{\partial \theta^j}{\partial y^i} dy^j \tag{15}$$

It should be noted that $d\theta^i$ remains a contravariant vector under all transformations including transformations of coordinate systems in the deforming process. This is not the case with the covariant vector $d\theta_i$. Thus Eq. (11) is now written in general terms as

$$ds_0^2 = dx^i dx^i = g_{ij} d\theta^i d\theta^j$$

$$ds^2 = dy^i dy^i = G_{ij} d\theta^i d\theta^j \tag{16}$$

where g_{ij} and G_{ij} are the covariant metric tensors of the two states of deformation under investigation. The functions are found for a given time t and are therefore functions of t as well as of $\theta_1, \theta_2, \theta_3$. These functions are mathematically defined as follows:

$$g_{ij} = \frac{\partial x^m}{\partial \theta^i} \frac{\partial x^m}{\partial \theta^j} \quad , \quad g^{ij} = \frac{\partial \theta^i}{\partial x^m} \frac{\partial \theta^j}{\partial x^m} \tag{17}$$

with an example expansion:

$$g_{11} = \frac{\partial x^1}{\partial \theta^1} \frac{\partial x^1}{\partial \theta^1} + \frac{\partial x^2}{\partial \theta^1} \frac{\partial x^2}{\partial \theta^1} + \frac{\partial x^3}{\partial \theta^1} \frac{\partial x^3}{\partial \theta^1}$$

g_{ij} = etc., to give a determinant

$$g = |g_{ij}| = \begin{vmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{vmatrix}$$

and

$$G_{ij} = \frac{\partial y^m}{\partial \theta^i} \frac{\partial y^m}{\partial \theta^j}, \quad G^{ij} = \frac{\partial \theta^i}{\partial y^m} \frac{\partial \theta^j}{\partial y^m} \tag{18}$$

with an example expansion:

$$G_{11} = \frac{\partial y^1}{\partial \theta^1} \frac{\partial y^1}{\partial \theta^1} + \frac{\partial y^2}{\partial \theta^1} \frac{\partial y^2}{\partial \theta^1} + \frac{\partial y^3}{\partial \theta^1} \frac{\partial y^3}{\partial \theta^1}$$

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G_{ij} = etc., to give a determinant

$$G = |G_{ij}| = \begin{vmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{vmatrix}$$

We now compare the distance ds_0 at P_0 with ds at P as follows:

$$ds^2 - ds_0^2 = (G_{ij} - g_{ij})\, d\theta^i\, d\theta^j \tag{19}$$

As stated in Eq. (6) the strain tensor is defined as

$$\varepsilon_{ij} = \frac{1}{2}(G_{ij} - g_{ij})$$

Now if a strain measurement experiment is performed that will measure in cartesian coordinates the strains at a point, both before and after deformation, then the magnitude of finite strain is to be computed from

$$\begin{aligned}
\varepsilon_{11} &= \frac{\partial u_1}{\partial x_1} + \frac{1}{2}\left\{\left(\frac{\partial u_1}{\partial x_1}\right)^2 + \left(\frac{\partial u_2}{\partial x_1}\right)^2 + \left(\frac{\partial u_3}{\partial x_1}\right)^2\right\} \\
\varepsilon_{22} &= \frac{\partial u_2}{\partial x_2} + \frac{1}{2}\left\{\left(\frac{\partial u_1}{\partial x_2}\right)^2 + \left(\frac{\partial u_2}{\partial x_2}\right)^2 + \left(\frac{\partial u_3}{\partial x_2}\right)^2\right\} \\
\varepsilon_{33} &= \frac{\partial u_3}{\partial x_3} + \frac{1}{2}\left\{\left(\frac{\partial u_1}{\partial x_3}\right)^2 + \left(\frac{\partial u_2}{\partial x_3}\right)^2 + \left(\frac{\partial u_3}{\partial x_3}\right)^2\right\} \\
\varepsilon_{12} &= \frac{1}{2}\left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1}\right) + \frac{1}{2}\left(\frac{\partial u_1}{\partial x_1}\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1}\frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_1}\frac{\partial u_3}{\partial x_2}\right) \\
\varepsilon_{23} &= \frac{1}{2}\left(\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}\right) + \frac{1}{2}\left(\frac{\partial u_1}{\partial x_2}\frac{\partial u_1}{\partial x_3} + \frac{\partial u_2}{\partial x_2}\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}\frac{\partial u_3}{\partial x_3}\right) \\
\varepsilon_{13} &= \frac{1}{2}\left(\frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1}\right) + \frac{1}{2}\left(\frac{\partial u_1}{\partial x_1}\frac{\partial u_1}{\partial x_3} + \frac{\partial u_2}{\partial x_1}\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_1}\frac{\partial u_3}{\partial x_3}\right)
\end{aligned} \tag{20}$$

where

x_1, x_2, x_3 = undeformed cartesian base frame

u_1, u_2, u_3 = corresponding displacements with respect to x_1, x_2, x_3.

Note that Eq. (7) may be obtained by neglecting the shear terms in Eq. (20).

5. Point Strains Versus Structural Strains

The mathematics presented above describes point strain phenomena. Experiments performed in a laboratory are usually concerned with the over-all displacements of a structure. Regardless of the over-all dimensions of a specimen, it is usually loaded as a structure. That is to say, simple loadings are difficult to apply. Usually the experimentalist neglects the boundary strains due to bending, shear, and torsion by the St. Venant Principle. It is a common practice to assume that structurally determined strains are equivalent to intrinsic point strains because of expediency. In practice there is a tendency to confuse structural analysis with basic point analysis. Whereas, to proceed from basic point analysis to structural analysis is correct, the converse is not necessarily true. An obvious example is that of a deformed beam. Here the strain can be computed knowing the stress at a point using basic point analysis. However, the stress determination at the point is determined from geometric considerations prevalent to structural analysis.

A more pertinent example is illustrated by biaxially pressurizing an unrestricted propellant grain. Here an over-all longitudinal contraction might experimentally be expected. Nevertheless an unusual barreling structural deformation occurs with a consequential end effect (Fig. 11). To indicate that the over-all longitudinal contraction measures an average point strain is analogous to assuming that a cube deforms into a rhombohedron instead of a curvilinear parallelepiped in a shear experiment.

In summary it is noted that a line constructed of points in or on an undeformed body (structure) will usually become skew upon deformation of the body. Consequently, if a cartesian coordinate system is chosen for the curvilinear system θ^i in the undeformed state, it will in general be difficult to express the structural boundary conditions because the structure will be transformed into a natural curvilinear system ψ^i. Thus, except for specific experiments such as described by Rivlin (Ref. 27), the mathematical concepts of strain presented above become unwieldy for practical experimental applications. However, if experimentally the principal strains can be measured in the close proximity of a point both before and after loading, this transformation difficulty is overcome from a practical (engineering) point of view. This is because at a point origin, the curvilinear strains in the deformed state approach in magnitude the cartesian strain (Fig. 13). It is for this reason that the photoelastic coating technique was developed for the study of propellant physical properties. No matter what contortions the over-all structure experiences, the photoelastic coating technique will only measure the biaxial principal strains at a point region on the structure.

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6. Strain Invariants

Utility of Eq. (1) is predicated on the usage of the proper strain invariants I_1, I_2, and I_3. A mathematical definition of the invariants is as follows:

$$I_1 = g^{rs}G_{rs} \;;\; I_2 = G^{rs}g_{rs}I_3 \;;\; I_3 = \frac{G}{g} \qquad (21)$$

A geometric description is evidently not obvious from Eq. (21). However, if one needed a schematic model to visualize these invariants, perhaps the notion of a particular set of three skew fibers that remained skew (invariant) under deformations may suffice. In Ref. 28, a good physical interpretation of strains is presented. Perhaps further study of this reference can lead to a better geometric notion of strain invariants.

Emphasis should be made that the strain invariants I_1, I_2, and I_3 must be derived for any particular class of deformation in accord with Eq. (21). In essence the general practice is to choose a structure and assume its strain state (note that this is quite complicated except for a point analysis).

The form of the invariants (I_1, I_2, and I_3) listed in Eq. (1) is only applicable to describe the straining of a cube into a cuboid. It is obvious that only cartesian coordinates would be considered to represent the material and spacial (Ref. 29) reference frames for this particular geometric deformation. Should a different kind of deformation be considered, then another description of the invariants would be in order (Ref. 26). Another advantage in using cartesian coordinates is that no distinction need arise between covariant and contravariant differentiation. Thus, the use of cartesian coordinates in the theory suggests that the three principal strains be experimentally measured in cartesian coordinates. Eq. (22) is obtained by differentiating the invariants defined in Eq. (1).

The magnitudes of these invariant gradients at a point may then be computed knowing the principal strains ($\varepsilon_1 = \varepsilon_{11}$, $\varepsilon_2 = \varepsilon_{22}$, $\varepsilon_3 = \varepsilon_{33}$):

$$\frac{\partial I_1}{\partial \varepsilon_1} = 2 + 2\varepsilon_1 \qquad \frac{\partial I_1}{\partial \varepsilon_2} = 2 + 2\varepsilon_2 \qquad \frac{\partial I_1}{\partial \varepsilon_3} = 2 + 2\varepsilon_3$$

$$\frac{\partial I_2}{\partial \varepsilon_1} = 4 + 4\varepsilon_1 + 4\varepsilon_2 + 4\varepsilon_3 + 2\varepsilon_1\varepsilon_2^2 + 2\varepsilon_1\varepsilon_3^2 + 4\varepsilon_1\varepsilon_2 + 4\varepsilon_3\varepsilon_1 + 2\varepsilon_2^2 + 2\varepsilon_3^2$$

$$\frac{\partial I_2}{\partial \varepsilon_2} = 4 + 4\varepsilon_1 + 4\varepsilon_2 + 4\varepsilon_3 + 4\varepsilon_1\varepsilon_2 + 4\varepsilon_2\varepsilon_3 + 2\varepsilon_1^2\varepsilon_2 + 2\varepsilon_2\varepsilon_3^2 + 2\varepsilon_1^2 + 2\varepsilon_3^2$$

$$\frac{\partial I_2}{\partial \varepsilon_3} = 4 + 4\varepsilon_1 + 4\varepsilon_2 + 4\varepsilon_3 + 4\varepsilon_2\varepsilon_3 + 4\varepsilon_1\varepsilon_3 + 2\varepsilon_3\varepsilon_2^2 + 2\varepsilon_1^2\varepsilon_3 + 2\varepsilon_2^2 + 2\varepsilon_1^2$$

$$\frac{\partial I_3}{\partial \varepsilon_1} = 2 + 4\varepsilon_2 + 2\varepsilon_2^2 + 2\varepsilon_1 + 4\varepsilon_2\varepsilon_1 + 2\varepsilon_1\varepsilon_2^2 + 4\varepsilon_3 + 8\varepsilon_2\varepsilon_3 + 4\varepsilon_3\varepsilon_2^2 + 4\varepsilon_1\varepsilon_3 + 8\varepsilon_2\varepsilon_3\varepsilon_1 + 4\varepsilon_1\varepsilon_3\varepsilon_2^2 + 2\varepsilon_3^2 + 4\varepsilon_2\varepsilon_3^2 + 2\varepsilon_2^2\varepsilon_3^2 + 2\varepsilon_1\varepsilon_3^2 + 4\varepsilon_2\varepsilon_1\varepsilon_3^2 + 2\varepsilon_1\varepsilon_2^2\varepsilon_3^2 \qquad (22)$$

$$\frac{\partial I_3}{\partial \varepsilon_2} = 2 + 2\varepsilon_2 + 4\varepsilon_1 + 4\varepsilon_1\varepsilon_2 + 2\varepsilon_1^2 + 2\varepsilon_1^2\varepsilon_2 + 4\varepsilon_3 + 4\varepsilon_2\varepsilon_3 + 8\varepsilon_1\varepsilon_3 + 8\varepsilon_1\varepsilon_3\varepsilon_2 + 4\varepsilon_3\varepsilon_1^2 + 4\varepsilon_2\varepsilon_3\varepsilon_1^2 + 2\varepsilon_3^2 + 2\varepsilon_2\varepsilon_3^2 + 4\varepsilon_1\varepsilon_3^2 + 4\varepsilon_1\varepsilon_2\varepsilon_3^2 + 2\varepsilon_1^2\varepsilon_3^2 + 2\varepsilon_1^2\varepsilon_2\varepsilon_3^2$$

$$\frac{\partial I_3}{\partial \varepsilon_3} = 2 + 4\varepsilon_2 + 2\varepsilon_2^2 + 4\varepsilon_1 + 8\varepsilon_1\varepsilon_2 + 4\varepsilon_1\varepsilon_2^2 + 2\varepsilon_1^2 + 4\varepsilon_2\varepsilon_1^2 + 2\varepsilon_1^2\varepsilon_2^2 + 2\varepsilon_3 + 4\varepsilon_2\varepsilon_3 + 2\varepsilon_3\varepsilon_2^2 + 4\varepsilon_1\varepsilon_3 + 8\varepsilon_1\varepsilon_2\varepsilon_3 + 4\varepsilon_1\varepsilon_3\varepsilon_2^2 + 2\varepsilon_1^2\varepsilon_3 + 4\varepsilon_2\varepsilon_3\varepsilon_1^2 + 2\varepsilon_1^2\varepsilon_2^2\varepsilon_3$$

Consider the mathematical simplifications introduced by using point cartesian strain invariants and restrict the investigation to orthogonal coordinates, where the three families of coordinate surfaces are mutually perpendicular. If the experimental measurements are made at a point in cartesian coordinates, then an approximation can be made of the magnitudes associated with an appropriate curvilinear coordinate frame at that point. Integration from point to point using analytical theory in curvilinear coordinates would then yield the stress-strain response of the structure being studied. It is evident that the only reason a curvilinear system is chosen at some point in space is because it is simpler to express the boundary conditions of the vector field in natural coordinates. There is no reason to generalize the use of a curvilinear coordinate system for structure of arbitrary shape, e.g., a propellant cylinder.

7. A Proposed Analytical Description of the Strain Energy Function W

The strain energy function W, as its name would imply, is the amount of recoverable energy (in.-lb/in.^{3} = psi) stored in a deformed volume. From a mathematical point of view, W may be considered as an analog equivalent of the Lamé constants in linear elastic theory.

Prior to attempting to characterize W, the magnitudes of Ю, И and Я in Eq. (3) must be obtained. Since the

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point principal stresses are available using Eq. (4), Eq. (3) may be rewritten for a homogeneous deformation in terms of the principal cartesian strains as

$$\tau_{11} = \frac{1}{\sqrt{I_3}}\left\{Ю\frac{\partial I_1}{\partial \varepsilon_{11}} + И\frac{\partial I_2}{\partial \varepsilon_{11}} + Я\frac{\partial I_3}{\partial \varepsilon_{11}}\right\}$$

$$\tau_{22} = \frac{1}{\sqrt{I_3}}\left\{Ю\frac{\partial I_1}{\partial \varepsilon_{22}} + И\frac{\partial I_2}{\partial \varepsilon_{22}} + Я\frac{\partial I_3}{\partial \varepsilon_{22}}\right\} \qquad (23)$$

$$0 = \frac{1}{\sqrt{I_3}}\left\{Ю\frac{\partial I_1}{\partial \varepsilon_{33}} + И\frac{\partial I_2}{\partial \varepsilon_{33}} + Я\frac{\partial I_3}{\partial \varepsilon_{33}}\right\}$$

If at a point ε_{11}, ε_{22}, ε_{33} are measured explicitly so that the invariant gradients can be calculated, and τ_{11}, τ_{22} are calculated from the pressure and the cylindrical dimensions according to Eq. (4) then these data can be utilized in Eq. (23) to solve for Ю, И, Я.

The proper mathematical characterization of W is subjective. The simplest characterization would be to expand $W(I_1, I_2, I_3)$ in a Taylor series about $I_1 = 3$, $I_2 = 3$, $I_3 = 1$, for $W = 0$, and arbitrarily neglect higher order derivatives. The functional form would then be somewhat more general than existing proposed forms[3]:

$$W = Ю(I_1 - 3) + И(I_2 - 3) + Я(I_3 - 1) \qquad (24)$$

The mode of W versus I_1, W versus I_2 and W versus I_3 should indicate what the functional form of W could be for any specific propellant. Experimentally, therefore, the problem of finding W is reduced to one of finding the three principal strains at a point on the surface of a cylinder.

8. Computer Solutions of Photoelastic Coating Strains

Since the immediate interest concerns tubular unrestricted propellant grains, the graphical separation of the principal stresses measured in the bonded photoelastic coatings at various points have been programmed. In previous reports (*QSR* 38-3 through 38-9) a graphical technique was utilized. This same technique is the basis of the computer solution. Having established that the plane stress condition exists in a photoelastic coating, the principal stresses are separated as follows. The resulting shear stress σ_ψ at a point in a general two-dimensional stress system may be expressed as

$$\sigma_\psi = \frac{\sigma_{11} - \sigma_{22}}{2}\sin 2\psi - \sigma_{12}\cos 2\psi \qquad (25)$$

where ψ is the angle of rotation about a point with respect to the normal stress in the coating.

In retrospect it is noted that there is no shear along any radial trace for a pressurized cylinder because of symmetry. Therefore, Eq. (25) reduces to

$$\sigma_\psi = \frac{\sigma_{11} - \sigma_{22}}{2}\sin 2\psi \qquad (26)$$

for any point along a radial trace. Next, n equally spaced inspection points on the coating along one radial trace are selected. About these inspection points a plane element dr, $rd\theta$, is designated. In the limit this element approaches dx, dy (Fig. 13). By arbitrarily choosing $\psi = 1$ deg, Eq. (26) can be applied at the edge of the element to obtain a shear parallel to the radius $\theta = 90$ deg (Fig. 13). Thus with respect to a point i in the cartesian system, Eq. (26) becomes

$$\overset{i}{\sigma}_{xy} = 0.01745\,[\sigma_{11} - \sigma_{22}]_i \qquad (27)$$

The magnitude of $[\sigma_{11} - \sigma_{22}]_i$ is obtained directly from the previously calibrated isochromatic spectrum that corresponds to the point i under investigation.

It is necessary to reference the shear stress $\overset{i}{\sigma}_{xy}$ with respect to the axis of the cylinder. In this manner the fringe value of the isochromatic trace (in psi) can be directly assigned to Eq. (27), since the trace is originally measured with reference to the cylinder axis. In cartesian coordinates the distance x from a point on the reference radius ($\theta = 90$ deg) to the shear stress σ_{xy} may be expressed as

$$x_i = 0.01746\,[y_n + \delta(n - i)] \qquad (28)$$

where

y_i = radial distance to point

y_n = innermost point (its magnitude is equal to the number of points under investigation)

δ = equal increment $(y_1 - y_n)/(n - 1)$

[3]It is noted that by including the higher order derivatives and factoring the invariants, generalization of Ю, И, and Я as functions of I_1, I_2, and I_3 is possible.

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In the close proximity of the point under investigation (noting that $\overset{i}{\sigma}_{xy} = 0$ at $x_i = 0$) the shear $\overset{i}{\sigma}_{xy}$ with respect to x_i may be approximated in incremental form

$$\frac{\Delta \overset{i}{\sigma}_{xy}}{\Delta x_i} \approx \frac{d\overset{i}{\sigma}_{xy}}{dx_i} \tag{29}$$

From the two-dimensional equilibrium equation it is noted that

$$\frac{\partial \overset{i}{\sigma}_{yy}}{\partial y_i} = -\frac{\partial \overset{i}{\sigma}_{xy}}{\partial x_i} \tag{30}$$

so that the desired quantities $\partial \overset{i}{\sigma}_{yy}/\partial y_i$ are obtained.

The relationship between $\overset{i}{\sigma}_{yy}$ and y_i can be obtained on a computer using Simpson's rule, knowing the boundary conditions $\overset{i}{\sigma}_{yy} = 0$ at y_1. Separation of the principal stresses from isochromatic data is thus achieved knowing the calibrated stress-strain relationship of the linear coating.

The principal strains in the coating are then computed from

$$\begin{aligned} \overset{i}{\varepsilon}_{11} &= \left[\frac{\sigma_{11}}{E} - \frac{\mu}{E}\sigma_{22}\right]_i \\ \overset{i}{\varepsilon}_{22} &= \left[\frac{\sigma_{22}}{E} - \frac{\mu}{E}\sigma_{11}\right]_i \end{aligned} \tag{31}$$

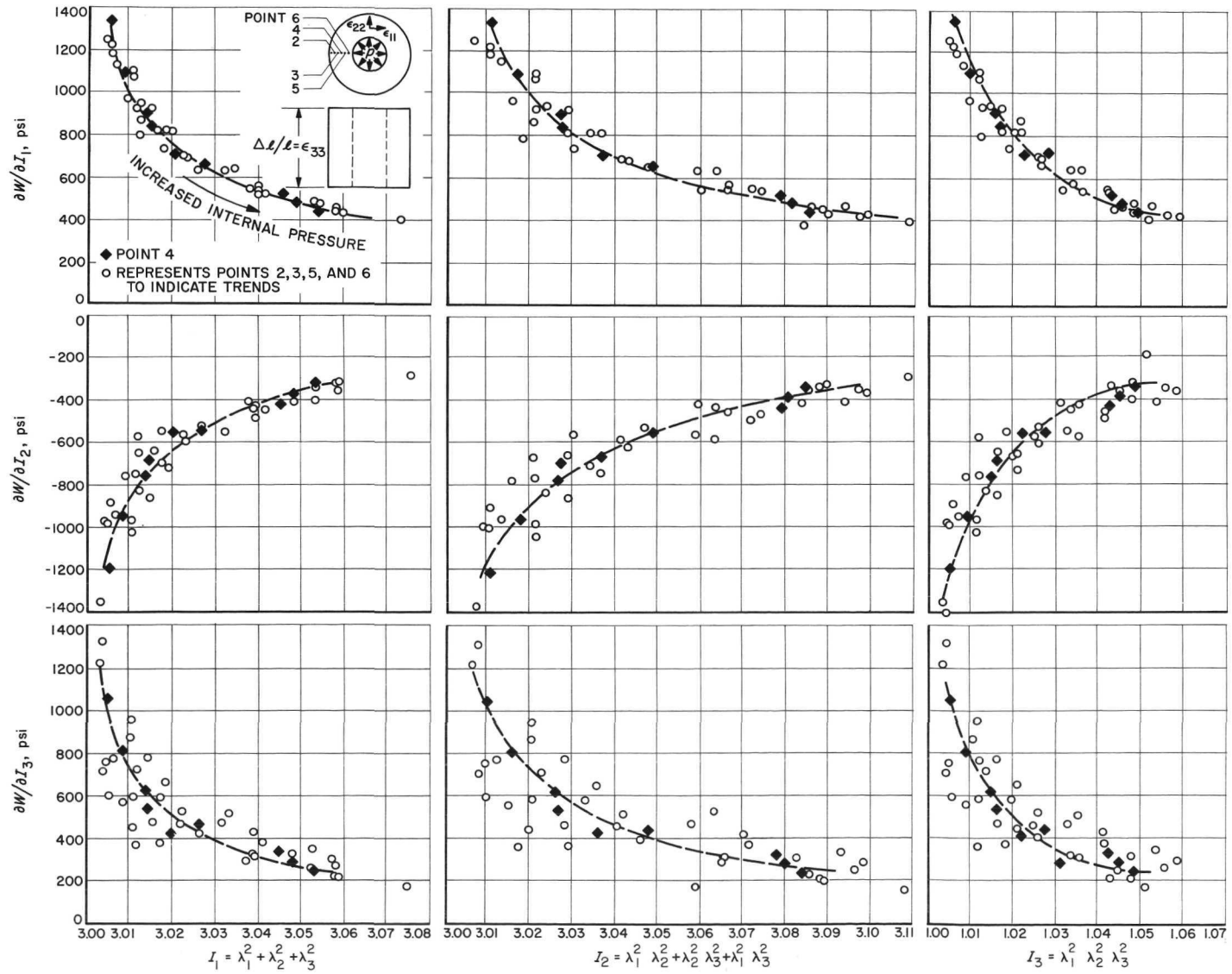

Fig. 16. Potential gradients versus the three invariants at points under varying stresses

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From Eq. (31) the magnitudes of the principal strains ε_{11} and ε_{22} can be obtained and stored in the computer's memory to be used later to compute the invariant gradients Eq. (22).

9. Measurement of Longitudinal Structural Strain

The discrepancy between ideal and actual structural deformation is exaggeratedly shown in Fig. 11. Attention is brought to the difficulties encountered with the measurement of a point longitudinal strain. An extensometer capable of examining the end effect was used to measure a structural strain. The applicability of this strain to the theory is questionable. However, it was found that the magnitude of this longitudinal principal strain was small compared to the biaxial principal strains. Thus, it is presumed that no appreciable error was introduced in this instance because of the use of a structural strain instead of a point strain. The longitudinal extensometer is illustrated in Fig. 12. The reflective polariscope and loading fixture are described in *QSR 38-9*.

10. The Strain Energy Function

The structural strain ε_{33} was only measured at Point 4 (Fig. 16) (center of the coating). Its numerical value was arbitrarily assigned to the other points for strain energy computations, i.e., as though there had been a uniform change in length. Fig. 11 denotes that this assignment is not precise because of the end effect of the cylinder. Biaxial strain data ε_{11} and ε_{22} obtained at Points 2 and 6 are also questionable because of their proximity to the coating edge and also because of cylinder end curvature. Therefore, only Point 4 is considered accurate. The other points are presented only as indicators of trends.

The potential gradients Ю, И, and Я, computed from Eq. (23), are plotted with respect to the invariants I_1, I_2, and I_3 in Fig. 16. A gradient-invariant relationship is shown for Points 2 through 6. A similar mode is observed for each of the nine relationships between the gradients and invariants.

The strain energy function W was assumed to be defined by Eq. (24). Figure 17 illustrates the values (subject to the limitations stated above) of W at the various points for the different stress-strain environments. As one would expect, the strain energy increases with effective strain. At Point 4 the three-dimensional strain energy approaches

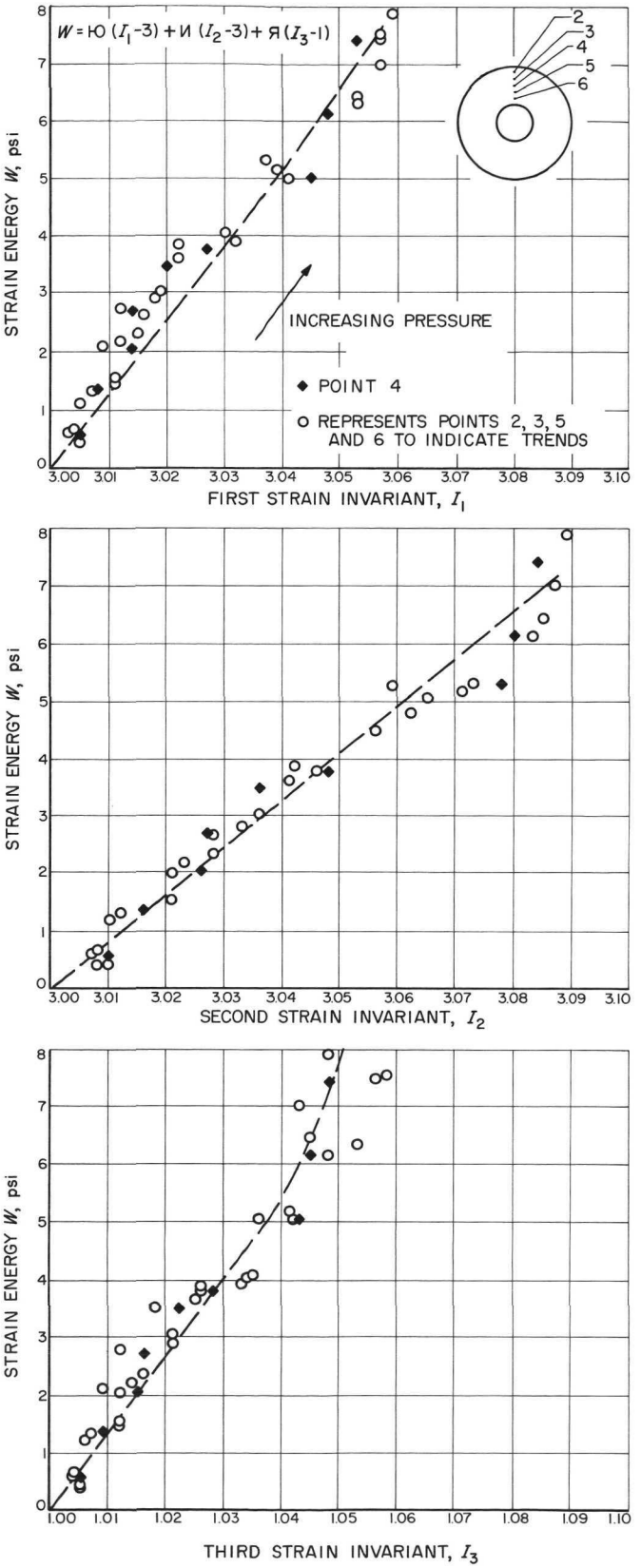

Fig. 17. Strain energy versus the three invariants at points under varying stresses

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7.4 psi for a strain field $\varepsilon_{11} = 0.089$, $\varepsilon_{22} = -0.052$, $\varepsilon_{33} = -0.016$, and a stress field $\tau_{11} = 76.1$ psi, $\tau_{22} = -15.4$ psi, $\tau_{33} = 0$.

It is noted that no control over the invariants could be made with this experiment. Only the internal pressure in the cylinder could be varied. The measured strain state at any arbitrary point on the cylinder depends only on the applied stresses at that point. The strain response of the medium to these stresses determines the potential gradients at the point. The variation of the gradients from point to point, therefore, arises from variation between the individual principal strains. The most significant variance, obviously, was between the radial and circumferential strains in the radial direction.

Finally, the question as to the credibility of the value obtained for the three-dimensional strain energy Eq. (24) can be answered by comparison with uniaxial tensile data. Such data was obtained from a tensile bar cast from the same mix batch. Uniaxial strain energy is defined as

$$W_u = \int_0^{\varepsilon_{11}} \tau_{11}\, d\varepsilon_{11} \tag{32}$$

The magnitude of W (uniaxial) is obtained from the area under the stress-strain curve (neglecting losses). For $\varepsilon_{11} = 0.06, W = 2.8$ psi; $\varepsilon_{11} = 0.08, W = 4.6$ psi; $\varepsilon_{11} = 0.10$, $W = 6.7$ psi. Thus, it is demonstrated that the value obtained for the three-dimensional strain energy is reasonable for Point 4.

11. Summary

An experimental method to determine the strain energy function W in three dimensions for solid propellant has been presented. No assumptions regarding the propellant's physical properties are necessary to obtain the new nonlinear physical property W. The strain energy function for a polyurethane propellant appears to be characterized by

$$W = \text{Ю}\,(I_1 - 3) + \text{И}\,(I_2 - 3) + \text{Я}\,(I_3 - 1)$$

where Ю, И, and Я are the leading partial derivatives in a Taylor expansion of $W(I_1 I_2 I_3)$ about the point $I_1 = 3$, $I_2 = 3$, $I_3 = 1$, for $W = 0$. Conventional uniaxial experimental data independently confirms the order of magnitude of the strain energy function obtained from the above equation.

References

1. Moacanin, J., "Diisocyanate-Linked Polymers. I. Dilute Solution Properties of Toluene Diisocyanate-Extended Polypropylene Glycol," *Journal of Applied Polymer Science*, Vol. 1, pp. 272–282, 1959.
2. Grassie, N., *Chemistry of High Polymer Degradation Processes*, Butterworths Publications, London, 1956.
3. Treloar, L. R. G., *The Physics of Rubber Elasticity*, p. 85, Oxford University Press, New York, N. Y., 1958.
4. Flory, P. J., "Theory of Elastic Mechanisms in Fibrous Proteins," *Journal of the American Chemical Society*, Vol. 78, p. 5222, 1956.
5. Flory, P. J., and Daoust, H., "Osmotic Pressures of Moderately Concentrated Polymer Solutions," *Journal of Polymer Science*, Vol. 25, p. 429, 1957.
6. Orofino, T. A., and Flory, P. J., "Relationship of the Second Virial Coefficient to Polymer Chain Dimensions and the Interaction Parameters," *Journal of Chemical Physics*, Vol. 26, p. 1067, 1957.
7. Smith, T. L., "Dependence of the Ultimate Properties of a SBR Rubber on Strain Rate and Temperature," *Journal of Polymer Science*, Vol. 32, p. 99, 1958.

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